PL-TR--93-1028

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# THE 3.5-METER TELESCOPE ENCLOSURE



Michael H. Brady



April 1994

**Final Report**







**PHILLIPS LABORATORY**
**Lasers and Imaging Directorate**
**AIR FORCE MATERIEL COMMAND**
**KIRTLAND AIR FORCE BASE, NM 87117-5776**

PL-TR--93-1028

This final report was prepared by Phillips Laboratory, Kirtland Air Force Base, New Mexico, under Job Order 3647AB03. The Laboratory Project Officer-in-Charge was Captain Michael H. Brady (LIG).



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# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



**1. AGENCY USE ONLY** *(Leave blank)*

**2. REPORT DATE**
April 1994

**3. REPORT TYPE AND DATES COVERED**
Final Report; 17 Aug 91 - 31 Mar 93

**4. TITLE AND SUBTITLE**
THE 3.5-METER TELESCOPE ENCLOSURE

**5. FUNDING NUMBERS**
PE: 63605F
PR: 3647
TA: AB
WU: 03

**6. AUTHOR(S)**
Michael H. Brady

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
Phillips Laboratory
3550 Aberdeen Avenue SE
Kirtland AFB, NM 87117-5776

**8. PERFORMING ORGANIZATION REPORT NUMBER**
PL-TR--93-1028

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**

**10. SPONSORING/MONITORING AGENCY REPORT NUMBER**

**11. SUPPLEMENTARY NOTES**

**12a. DISTRIBUTION/AVAILABILITY STATEMENT**
Approved for public release; distribution is unlimited.

**12b. DISTRIBUTION CODE**

**13. ABSTRACT** *(Maximum 200 words)*

The 3.5-m telescope enclosure is designed to perform two functions as part of the U.S. Air Force's 3.5-m telescope system: (1) to provide weather and temperature protection when the telescope is not in use and (2) to permit open-air operation of the telescope while minimizing atmospheric disturbances in the field of view (FOV). The use of a standard rotating dome is impractical because of the large telescope and its high rotational rate and acceleration. The enclosure is a 40-ft tall cylinder with a diameter of 72 ft. This steel and aluminum structure does not rotate but collapses vertically to fully expose the telescope to the open air and to provide it with an unobscured view of the horizon at all azimuthal angles. To lessen wind disturbances in the FOV, the enclosure has a moderately sloped roof and smooth, vertical walls. To minimize thermal flow, the outer surface has a high-reflectivity, low-emissivity coating and ambient air is forced through the double-skinned walls and roof. These measures make it possible to keep the enclosure surface temperature near that of the ambient air during viewing. With these features, the enclosure adds minimal degradation to the seeing.

**14. SUBJECT TERMS**
Telescopes, Domes, Structures

**15. NUMBER OF PAGES**
28

**16. PRICE CODE**

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| Unclassified | Unclassified | Unclassified | |

## ACKNOWLEDGEMENTS

The 3.5-m telescope enclosure project was a design, fabrication, and installation effort of the Special Projects Group of Coast Steel Fabricators, Ltd., in Port Coquitlam, British Columbia. Coast Steel has a great deal of experience in designing and building telescope enclosures, including the facility and dome for the Canada-France-Hawaii 3.5-m telescope and the domes for both W.M. Keck Telescopes. This experience made possible completion of the entire 3.5-m telescope enclosure project in 18 months. In addition, the work of the engineers of Rockwell Power Systems and the technical personnel of the Phillips Laboratory Propagation Branch cannot be overlooked. These people were responsible for carefully reviewing the Coast Steel design and ensuring that the enclosure interface with the facility and telescope was readily accomplished.

# CONVERSION FACTORS

| | | |
|---|---|---|
| 1 ft | = | 0.3048 m |
| 1 in | = | 25.4 mm |
| 1 hp | = | 0.746 kW |
| 1 lb | = | 4.448 N |
| 1 mph | = | 0.447 m/s |
| 1 Btu/hr | = | $2.93 \times 10^{-4}$ kW |

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## FIGURES

## 1.0 INTRODUCTION

The 3.5-m telescope is the cornerstone of a new $30 million United States Air Force research facility installed in late 1992 at the Starfire Optical Range (SOR) on Kirtland Air Force Base in Albuquerque, New Mexico. This telescope is a state-of-the-art optical instrument for research in atmospheric compensation and adaptive optics techniques. Many features, including active mirror support and precise mirror temperature control, have been incorporated in the telescope to permit optimal performance of the imaging system. However, one element of the system with the potential to either enhance or degrade this performance is not a telescope component at all. This element, the 3.5-m telescope enclosure, will play a key role in lessening the degrading effects of wind and thermal flows on telescope performance.

The fundamental purpose of any enclosure is to protect the telescope and its support equipment from the weather. The standard hemispherical dome with a narrow slit performs this task admirably; however, the typical dome is also a major contributor to "seeing," image blurring caused by nonuniform air temperature. Dome seeing has several sources including turbulence caused by the airflow across the slit as well as air density gradients caused by temperature differences between ambient air and the air inside the dome. The 3.5-m telescope enclosure, on the other hand, is designed to minimize atmospheric disturbances in the field of view caused by wind and thermal flows. When the telescope is not in use, the enclosure provides the requisite environmental protection. Then, prior to observing, this unique structure retracts to a position below the elevation axis that exposes the telescope completely to open air. Open-air operation of the telescope reduces the turbulence associated with large surrounding structures, thus reducing the turbulence problems to those inherent in the telescope structure.

## 2.0 STRUCTURAL DESIGN

The 3.5-m telescope enclosure is a cylindrical structure designed to retract vertically to a position that allows the telescope an unobscured view of the horizon at all azimuthal angles. This concept evolved from the Air Force requirement for an enclosure that would accommodate the high rotational rates and accelerations of the 3.5-m telescope. The telescope is capable of accelerating at up to 1.5 deg/s$^2$ to a maximum rate of 10.8 deg/s about its azimuth axis. The prospect of rotating a large enclosure at such accelerations and rates presents technical problems: the power requirement at the necessary acceleration is large, the enclosure serves as the source of undesirable mechanical and acoustic vibrations, and the enclosure cannot be stopped quickly in an emergency. Also, the work of Zago indicates that open-air operation of the telescope reduces enclosure-induced seeing degradation.[1] These factors led to the decision to develop a nonrotating, collapsible enclosure that would both accommodate the operational capability of the telescope and make use of the advantages of open-air operation.

The enclosure (Fig. 1) is a cylinder with a 15-deg sloping roof. In the fully raised position, the interior apex of the roof is 37 ft above the enclosure floor. The total height of the building and enclosure is 64 ft above ground level. In the lowered position, the top of the enclosure roof is only 10 ft above the enclosure floor, which allows the telescope a completely unobscured view of the horizon at all azimuthal angles. Inside the enclosure with the structure fully raised and the shutters closed, a clear radius of 27 ft exists about the azimuth axis of the telescope. The clear radius about the elevation axis is 19 ft; so, the telescope in its basic configuration (no instrumentation extending past the structure) can move through its full range of motion inside the closed enclosure. This capability is useful during operational testing and maintenance of the telescope.

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[1]Zago, L., "Design and Performance of Large Telescopes Operated in Open Air," Society of Photo-Optical Instrumentation Engineers, V. 628, pp. 350-359, 1986.

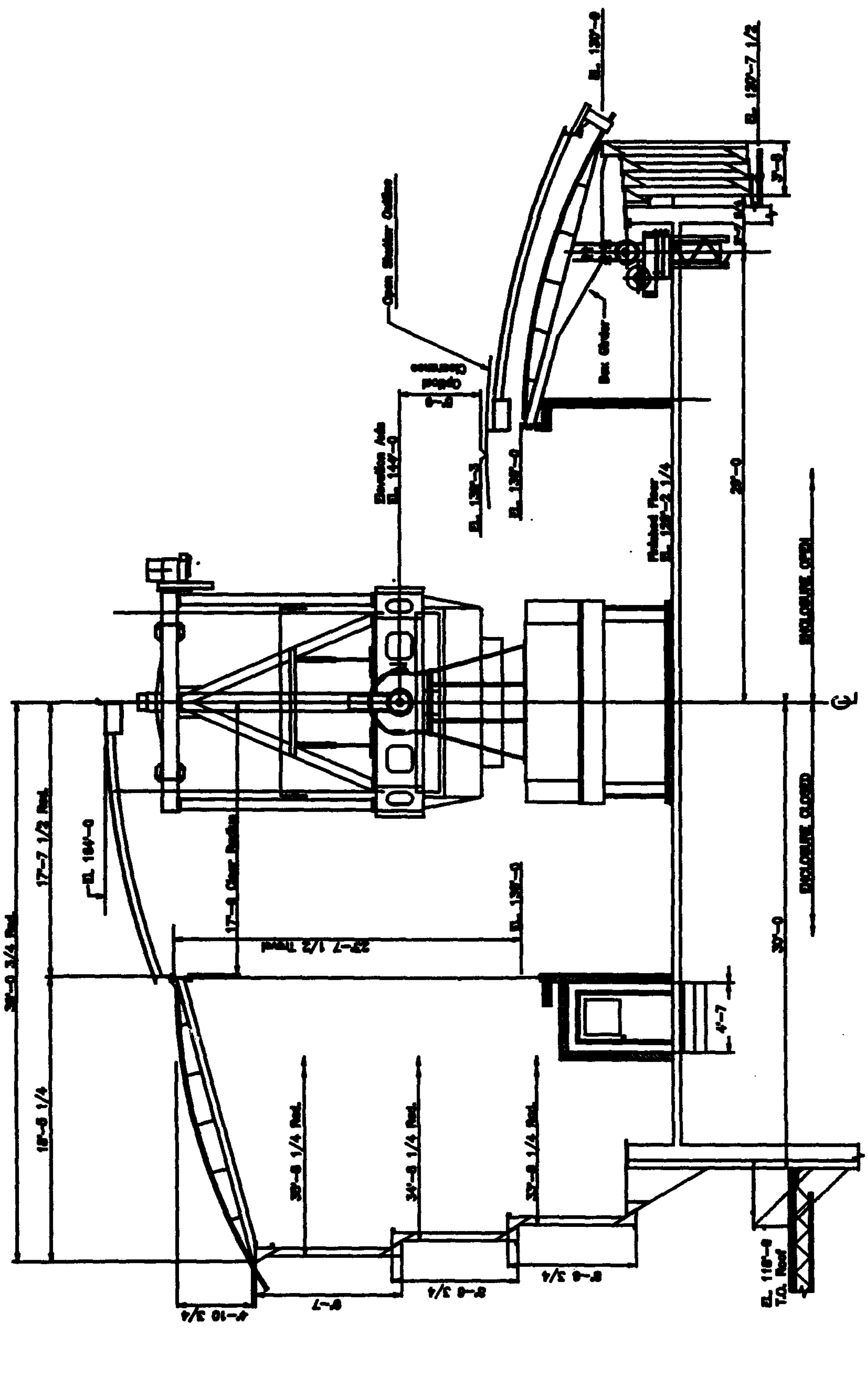

Figure 1. Section view of enclosure.

The roof opening that passes around the telescope when the structure is lowered has a clear radius of 17.5 ft. When the telescope is in its basic configuration, the enclosure can be lowered regardless of telescope elevation angle. However, if instrumentation is attached to the headring of the telescope, interference between the edge of the roof opening and the instrumentation is possible while the structure is being lowered or raised. For example, if a small acquisition telescope is attached to the headring, interference occurs when the 3.5-m telescope is positioned so that the acquisition telescope is on the side of the headring nearest the horizon and the elevation angle is between 20 and 42 deg from the horizon. However, the enclosure control system can include an interlock to prevent enclosure motion when interference is possible.

The enclosure cylinder consists of three wall segments. The bottom segment is 8.5 ft tall with an outer diameter of approximately 67 ft; the middle segment is 8.5 ft tall with a 69-ft diameter; and the top segment is 9.5 ft tall with a 71-ft diameter. The different diameters of the wall segments allow them to nest in a compact configuration when the structure is fully lowered, as shown in the right half of Figure 1. When the structure is raised, an inclined ring (30 deg from vertical) around the bottom edge of the upper segment meets a similar ring around the top edge of the middle segment, lifting that segment. In turn, the middle segment lifts the lower segment. This interface between wall segments is illustrated in Figure 2.

Each wall segment is composed of eight panels. Each panel has an inner and an outer skin separated by aluminum channels. The outer skin is 0.1575-in thick aluminum plate, while the inner skin is 0.0508-in thick (16 gauge) aluminum sheet. The 6-in gap between the skins acts as a clear path for convective and forced air flow. Vent holes in the inclined rings (described above) ensure that this flow is continuous from the bottom wall segment to the top segment. The air flow paths through the walls to the roof are indicated in Figure 3; the paths in the roof and shutters are shown in Figure 4.

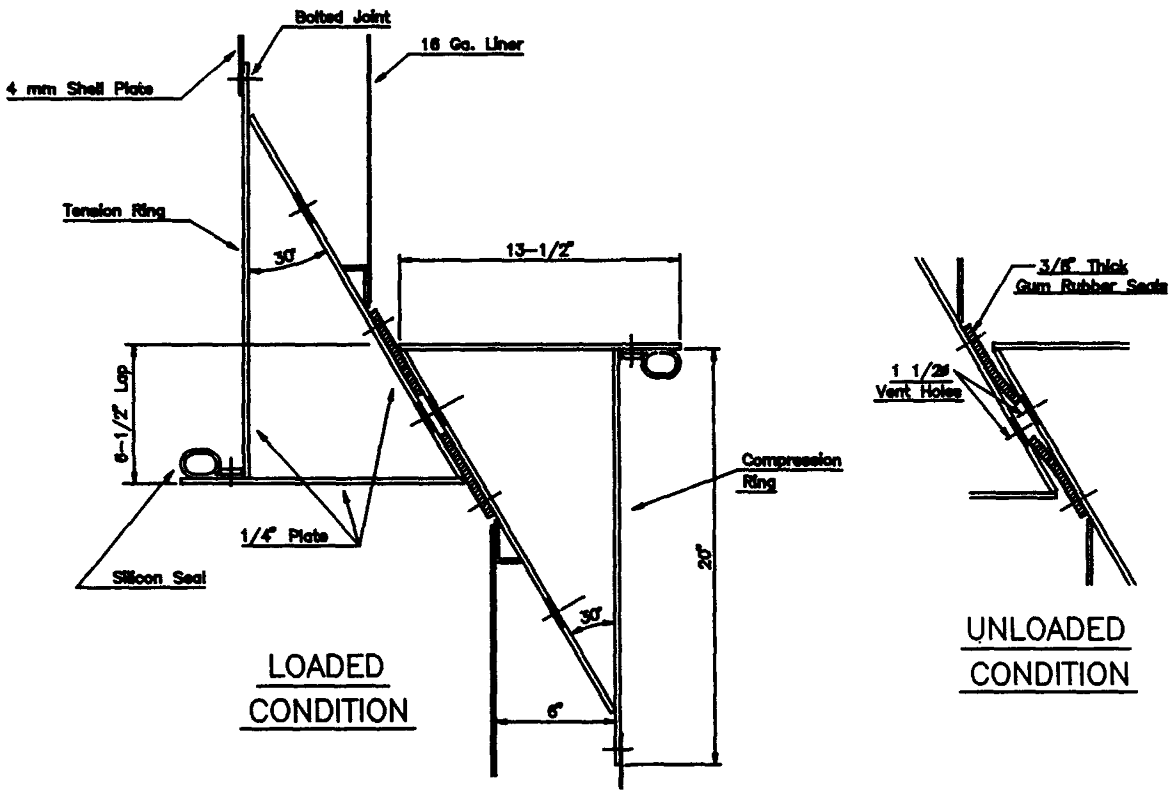


Figure 2. Section view of wall segment interface and seals.

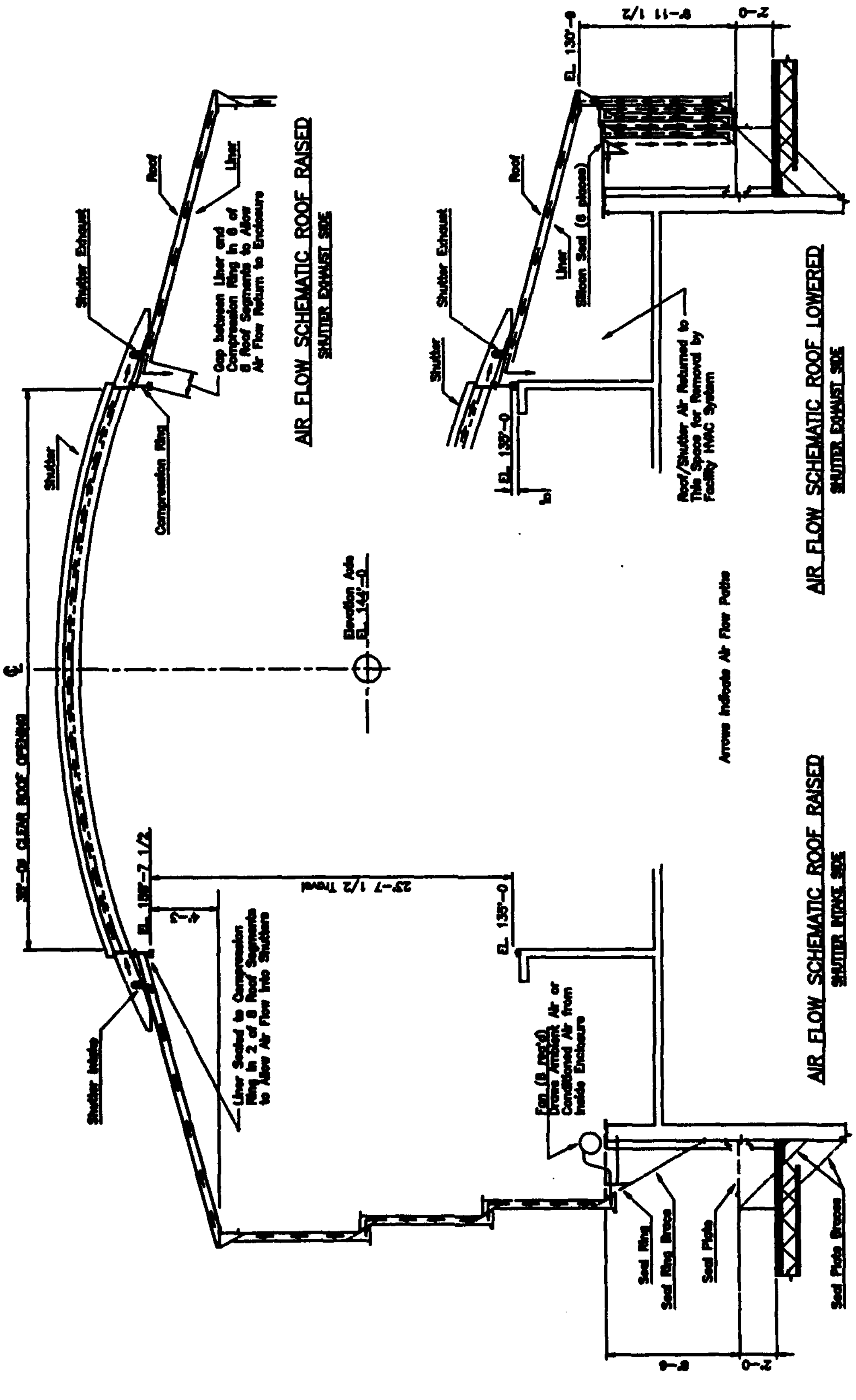


Figure 3. Schematic of air flow through walls to roof.

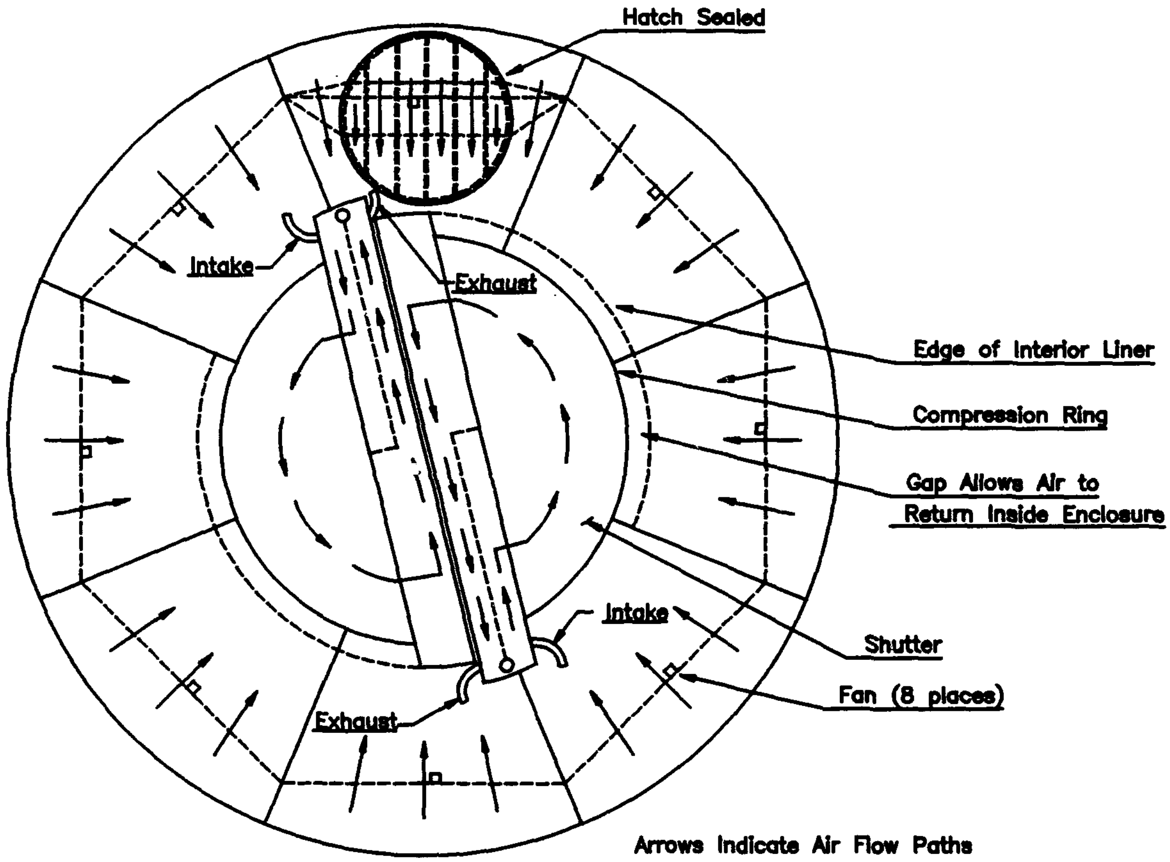


Figure 4. Schematic of air flow through roof to shutters.

The roof consists of the two shutters and eight sections of the same double-skinned construction as the wall panels. The roof sections are supported by eight steel box girders which extend radially from a compression ring around the central roof opening to a ring girder around the top of the upper wall segment. Vertical support for the enclosure is provided by columns attached to the box girders. Lateral stability is created by trusses that link each column and box girder to the adjacent columns and girders.

The two shutters, when closed, form a paraboloid which caps the central roof opening. The shutters, shown in Figure 5, are double-skinned with continuous air-flow passages. A 5-hp ball screw actuator drives each 7000-lb shutter as it swings open horizontally to allow the structure to retract around the telescope. The shutter is supported through its range of motion by its pivot and two guide rails, which ensure smooth operation and provide the support needed to meet all design loads.

An interesting feature of the enclosure is a 15-ft clear diameter hatch in the northernmost section of the roof (Fig. 5). Because the 3.5-m primary mirror must be recoated periodically, the hatch has been included to facilitate installation and removal of the mirror. Both removal of the hatch and lowering of the dome are steps used in an overall, very carefully orchestrated procedure to remove the 3.5-m primary mirror from the facility. Because the hatch cover can be removed or installed in less than 4-hr, the entire mirror installation or removal process can be completed in a single work day.

The enclosure is supported entirely by eight columns which extend 60 ft from the building foundation to the roof-support columns. Each support is a combination of a base column, a fixed column, and a sliding column. The base column is a 6-ft tall, 30-in diameter steel pipe embedded in the foundation. The fixed column, a welded lattice of steel L-shapes, is 26 ft tall with a 2 x 2-ft cross-section and is bolted to the top of the base column. This "lattice column" serves as a sleeve for the sliding column, which is a 36-ft-long steel box with a 1 x 1.5-ft cross-section. An elevator-type cable and pulley system moves the telescoping "box column" inside the lattice column.

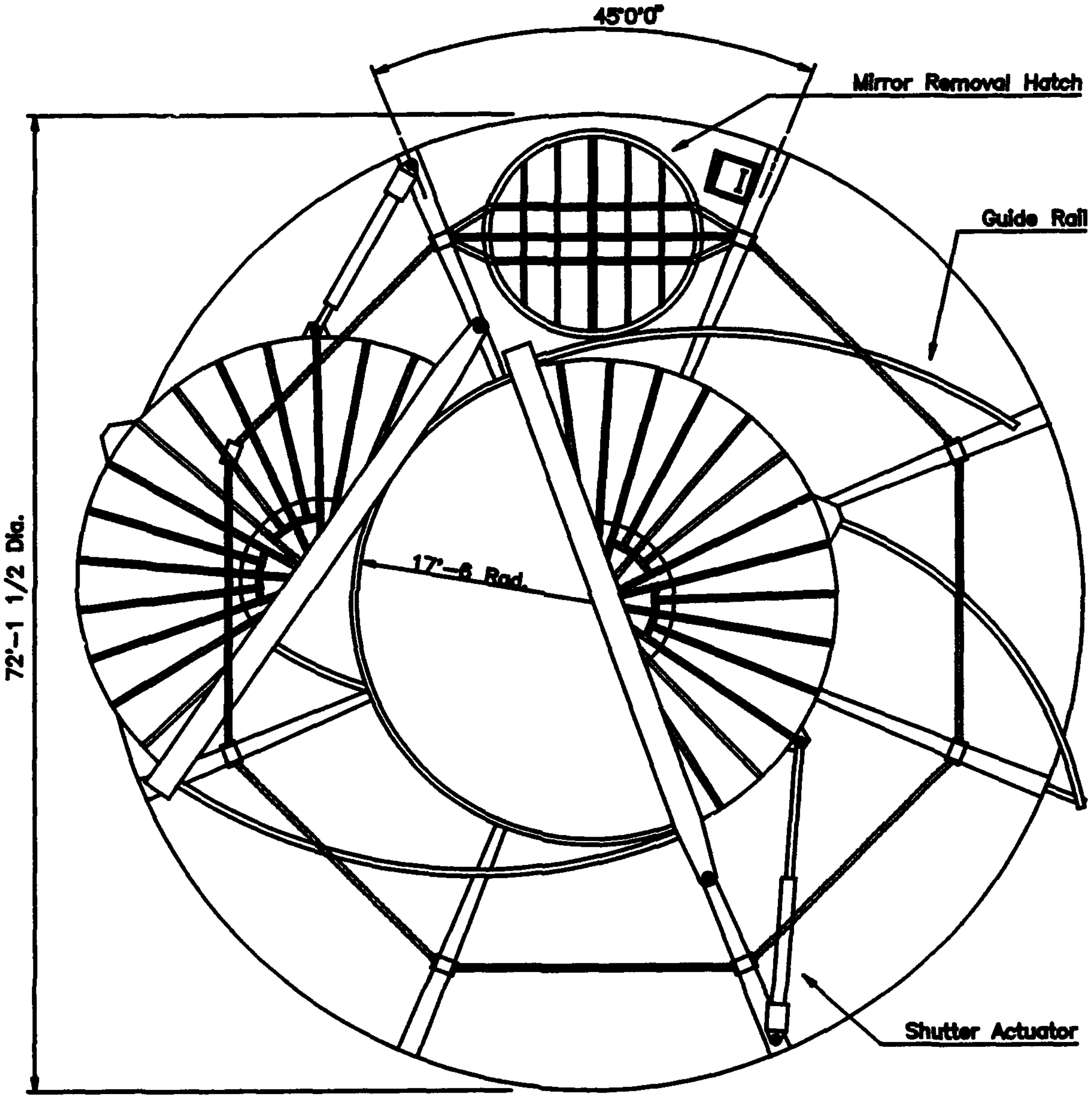


Figure 5. Top view of enclosure roof.

The entire steel and aluminum enclosure weighs approximately 143,000 lb, although the eight columns are capable of supporting up to 250,000 lb. In addition to the dead weight of the structure, the support system is designed to survive the load of a 120-mph wind and a 20-lb/ft$^2$ snow load. In fact, the enclosure can be raised in a 60-mph wind. Each lattice column is tied to the building walls to accommodate the lateral loads caused by wind. Also, in the fully extended position, 9 ft of each box column remain inside the lattice column sleeve. This overlap is a moment connection that enables the column to wit the overturning moment created by the wind load.[2] The moment connection limits th maximum flexure of any column under the 120-mph wind load to <3 in.

## 3.0 THERMAL DESIGN

The thermal characteristics of the enclosure received close scrutiny in the design process. If this project is to be successful ultimately, the enclosure must contribute considerably less degradation to the seeing than a classic dome. The basic thermal philosophy is to apply a coating to the outside surfaces that produces a reasonably good match between the temperature of the air and the dome structure. The double wall design permits management of residual heat transfer by cooling or ventilating this space.

The chief criterion for selection of a coating for the exterior surfaces is that the coating temperature must match ambient temperature. When this criterion is met, the exterior surface of the enclosure is as near equilibrium with ambient air as possible, and heat transfer through the field of view is at a minimum. However, an analysis of the thermal boundary layer[3,4]--the region in which temperature gradients exist[5]--reveals that heat transfer from

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[2]Brady, M., "3.5m Telescope Enclosure Design Review," Phillips Laboratory/LITE Internal Memorandum, 16 Dec 91.

[3]Holt, T., "Dome Design and Specification," Report No. 87-A/K-02-09-1423, R & D Associates, Albuquerque, New Mexico, 9 Nov 90.

[4]Incropera, F., and DeWitt, D., Introduction to Heat Transfer, Wiley, New York, 1985, pp. 288-294.

[5]Ibid., p. 248.

the enclosure surface does not affect the field of view except at elevation angles near horizontal. The assumptions of this analysis are that the flow is turbulent, the surface can be treated as a flat plate[6], and a temperature difference of 2°C exists between the surface and ambient air. Under these conditions, the thermal boundary layer does not intersect the field of view at elevation angles above 26 deg from the horizon for wind speeds above 1 mph. Therefore, heat transfer from the enclosure does not contribute to temperature gradients in the field of view under most wind conditions. The position of the thermal boundary layer relative to the shutter outline is shown in Figure 6. The curve in Figure 7 indicates, for a given wind speed, the elevation angle at which the thermal boundary layer just impinges on the field of view.

Three candidate coatings (3M #427 aluminum foil tape, white ceramic paint, and aluminized paint) were tested for their ability to match ambient temperature. Of these materials, the foil tape, which has a reflectivity of 0.8 and an emissivity of 0.2, demonstrated the best overall performance.[7] The data in Figure 8 show that the surface coated with foil tape became at most 8°C hotter than ambient air on a cool November day and matched ambient almost exactly during the cold night.[8] White paint (0.8 reflectivity, 0.9 emissivity) showed the best daytime response, only overheating by 6°C, but cooling to 3°C below ambient at night. The aluminized paint (0.7 reflectivity, 0.8 emissivity) sample showed poor performance in general, overheating by 13.5°C and undercooling by 2.5°C. However, these data only indicate the relative performance of the materials, as the temperature differences are magnified on hotter days and colder nights.

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[6]Ibid., p. 288.

[7]Beugelink, H., "Enclosure Heat Load," Letter to M. Brady, Coast Steel Fabricators, Ltd., Port Coquitlam, British Columbia, 25 Feb 92.

[8]Slavin, A., "3.5m Dome Material Test Results," Phillips Laboratory/LITE Internal Memorandum, 13 Feb 92.

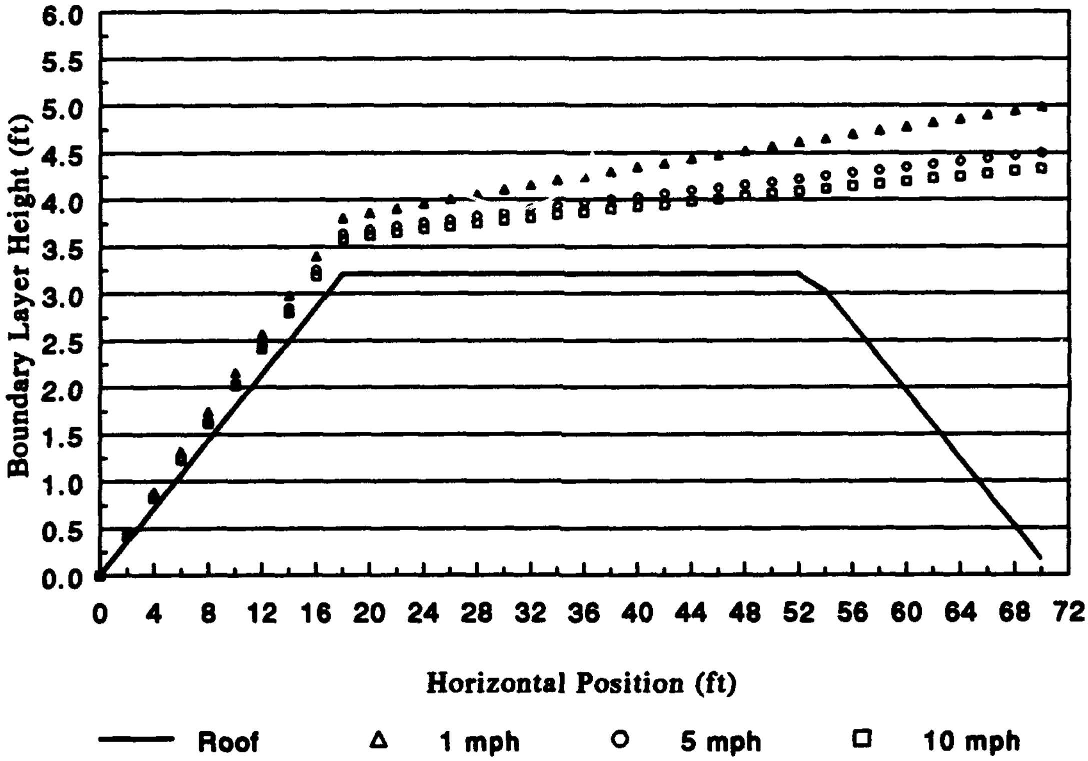


Figure 6. Thermal boundary layer profile on roof for 2°C ΔT.

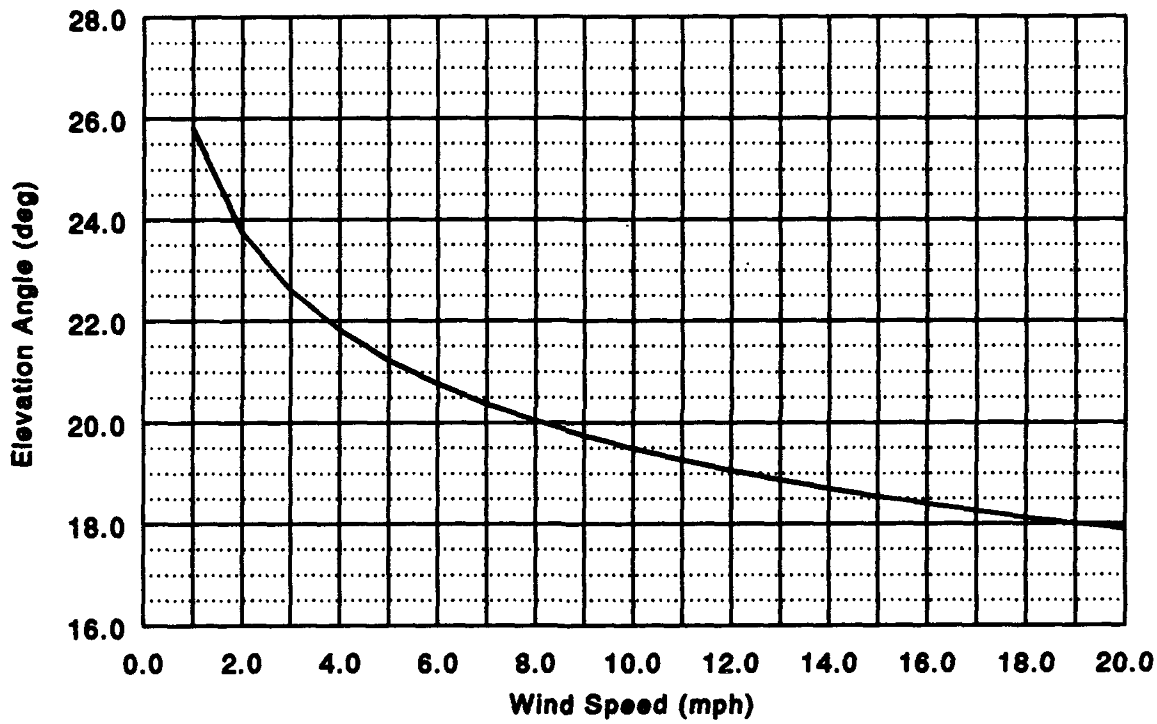


Figure 7. Elevation angle above which thermal boundary layer does not impinge upon field of view for 2°C $\Delta T$.

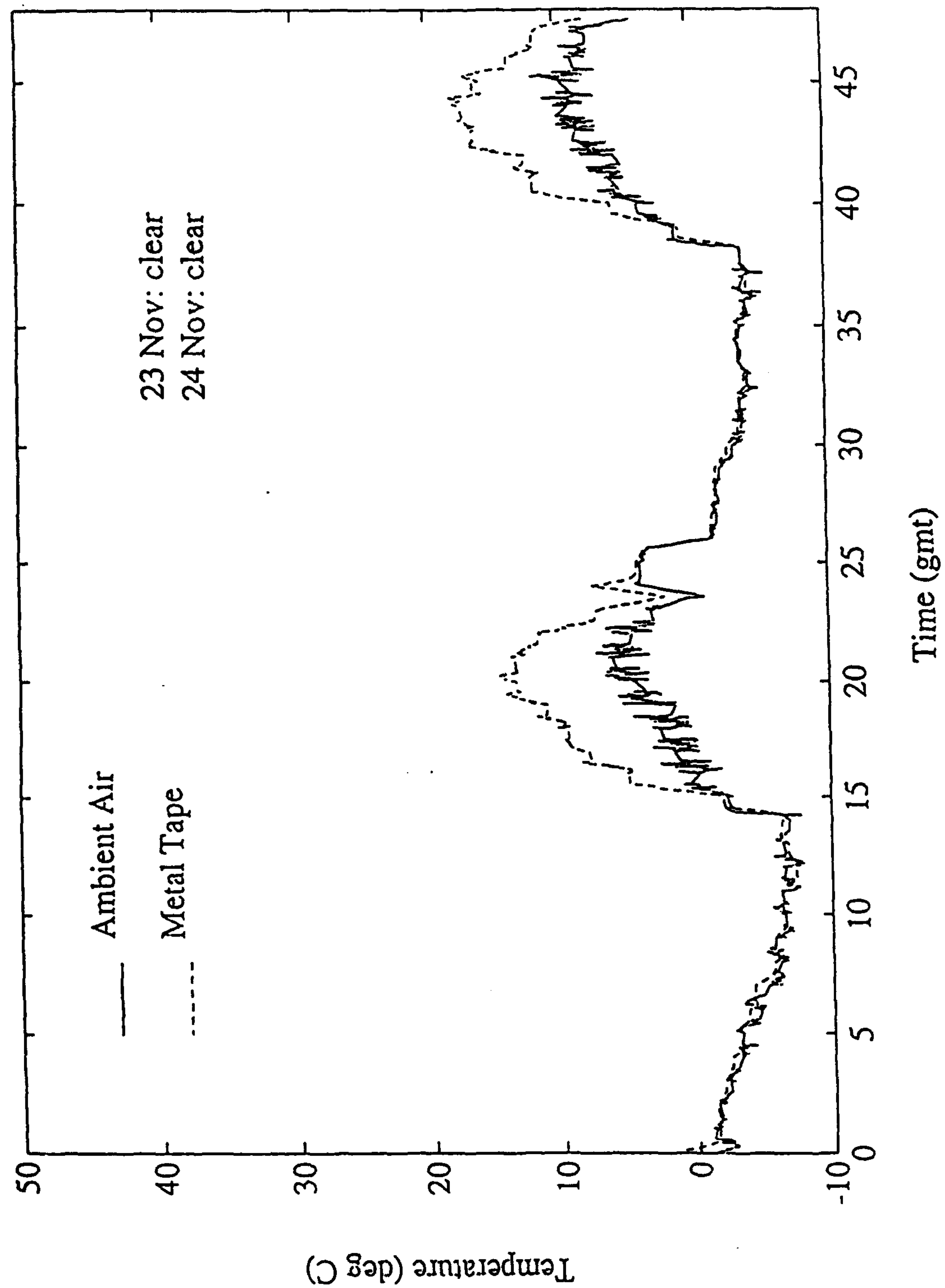


Figure 8. Ambient temperature matching characteristics of enclosure coating.

In addition to the surface-ambient air temperature difference, the temperature difference between ambient air and the air inside the enclosure is also important. This temperature difference manifests itself in a solar heat load on the enclosure, which must be removed by the facility air conditioning system. The design heat load on the enclosure in June is 123,500 Btu/hr. The enclosure thermal management system is designed to remove 70 percent of this heat by forcing conditioned air through the space between the wall, roof, and shutter skins.[9] As shown in Figure 3, the paths for this air flow are continuous in both the fully raised and lowered positions of the enclosure. The seals that prevent air from escaping at the wall segment interfaces are depicted in Figure 2.

The spaces inside the walls, roof, and shutters can be ventilated with either ambient air or conditioned air from inside the enclosure. A flow-direction box at each of the eight fans around the enclosure periphery is used to select the appropriate air flow source. Because constant conditioning of the space inside the walls taxes the facility air conditioning system, during most nonobserving periods ambient air is used to carry heat from the space inside the walls, roof, and shutters. Prior to observing, conditioned air is forced through the walls, roof, and shutter to bring the enclosure as close as possible to the anticipated night ambient temperature. Then, with the enclosure lowered, either forced ambient air or the natural reradiative properties of the coating are used to maintain this thermal equilibrium during observation. In all cases, the exhaust air is returned to the space inside the enclosure where it joins the air conditioning system air flow.

The enclosure structure acts as a barrier to heat transfer from the facility to the telescope during operation. The lowered structure mates with an annular wall around the base of the telescope, sealing all heat from electronics, the enclosure actuators, etc., beneath the roof. This heat is entrained in the air conditioning system air flow for removal. To ensure that no heat is rejected near the telescope, all exhaust air is finally released into the atmosphere approximately 300 ft from the facility.

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[9]Beugelink.

## 4.0 ACTUATION SYSTEM

The actuation system of the enclosure is designed to be rugged, efficient, relatively simple to operate, and safe. The eight actuators are modeled after the typical elevator-type cable and pulley system. Each actuator employs a single cable which has one end attached to the sliding column and the other end fixed to a rotating drum. The 10-hp variable speed motors that drive the drums operate on 208-V, 60-Hz, three-phase power. A programmable logic controller (PLC) uses alternating current frequency control to manage the motors.

A key concern in controlling enclosure motion is that a component failure must never make it impossible to raise the structure in an emergency. Many provisions have been made for fail-safe operation, including redundant sensors and mechanisms for manual actuation. Also, the enclosure must not bind or jam. Binding is possible if one of the actuating columns is considerably higher or lower than the others. However, the cables are somewhat flexible; so, binding is less likely than with a rigid actuation system, such as a gear drive.

In addition to the flexibility of the cables, the self-balancing feature of the actuation system makes binding or jamming of the enclosure unlikely. The system is self-balancing because the speed of a particular motor is dependent upon the load on that motor. In turn, the load is dependent upon the relative position of the particular column. If the enclosure is being raised, for example, the highest column supports more of the total enclosure load than the others. Because the load is greater, the corresponding motor will drive the column more slowly, allowing the other columns to catch up. This self-balancing nature is also useful for trouble-shooting the actuation system. If one column is higher or lower than the others by more than the allowable difference (approximately 0.75 in), the control system will stop actuation. The faulty drive unit can be disengaged for repair, and the remaining seven columns will raise or lower the enclosure.

## 5.0 OPERATION

There are four modes of enclosure operation. The normal mode features operation by a person at a control panel near the telescope. During operation in this mode, the PLC continuously regulates motor speeds and monitors the column positions (by means of an absolute optical encoder on each column), fault conditions, and assorted sensors. From a position at the control panel, the operator can visually check that no personnel or equipment are in dangerous locations when the enclosure is moving. The control panel includes separate structure and shutter controls, which are interlocked to prevent any motion of the structure when the shutters are not fully open and to prevent the shutters from closing when the structure is not fully raised. In the normal mode, opening or closing the shutters takes 2.8 min, and full travel of the structure (23 ft-7.5 in) is accomplished in 3.2 min.

The second and third modes of operation are "manual" modes, because the PLC does not play its normal role in controlling enclosure motion. In the "master manual" mode, operation is again initiated from the control panel near the telescope, but the PLC is bypassed. This mode allows the enclosure to be raised or lowered when a faulty sensor or switch interferes with normal operation. In the "local manual" mode, each actuator is independently operated via its own control panel. This mode is intended for use in maintenance and testing procedures. In both manual modes the enclosure moves at 30 percent of its normal speed.

The final mode is "emergency operation." This mode is intended for use in worst-case situations when all the actuation drives are inoperable (e.g., a complete power failure has occurred). Each drive is equipped with a crank that can be turned by portable pneumatic equipment. The shutter drives feature similar cranks. Although use of the emergency mode is difficult, it is the last resort for protecting the telescope if the enclosure fails.

# 6.0 SAFETY

Several safety features have been incorporated into the actuation system including emergency stop buttons, mechanical brakes, and large factors of safety used in design calculations. Emergency stop buttons are plentiful in the enclosure, and the circuit is designed to accommodate any number of additional buttons. To prevent these buttons from being used as convenient "start/stop" switches, the actuation system must be reset from the control panel any time an emergency stop is used. In addition, each button on the control panel is a dead-man switch, which must be held in the depressed position by the operator for the duration of enclosure motion. When the button is released, the enclosure travels no more than 6 in before stopping.

Each drive includes a mechanical brake that is disengaged only when that drive is commanded to operate. If power to the drive is interrupted, the brake returns to the closed position. This brake system prevents the enclosure from drifting or coasting after its motion has stopped. Because the structure can be positively stopped in any position, the enclosure can be used as a windscreen when the telescope is observing objects near zenith.

Finally, the enclosure as a whole was designed with safety as a primary consideration. For example, there is a factor of two safety in cable strength. Each cable has a breaking strength of 31,350 lb. The maximum design load is 250,000 lb (31,250 lb per column). However, because of the arrangement of the cable-pulley system, the tension in each cable is only half of the load on that particular column. Therefore, the theoretical load the combination of eight cable-pulley systems can support is 500,000 lb. The actual load is 143,000 lb. Also, the complete actuation system is designed so that seven of the columns can raise the enclosure. Both conservative design and redundant systems were applied to ensure that the enclosure protects the 3.5-m telescope under all foreseeable weather conditions.

## 7.0 CONCLUSION

The 3.5-m telescope enclosure is a typical enclosure in that it was designed for structural stability to ensure complete protection of the telescope. However, the enclosure is atypical in two ways. First, the structure has the unique capability to retract vertically for open-air operation of the telescope. Second, the smooth roof profile and the thermal management system minimize the degradation of local seeing caused by wind and thermal flows. These features make the enclosure an important component in the 3.5-m telescope system and a contributor to continued adaptive optics research at the Phillips Laboratory.

Although the enclosure was carefully designed, its operational characteristics will not be accurately quantified until experiments are performed under typical observing conditions. For instance, the enclosure thermal management system is critical for optimal telescope performance. To quantify the effectiveness of the system in reducing thermal flows through the field of view, local temperature variations on the enclosure surface must be mapped and the thermal boundary layer analysis must be supported with experimental data. To study the seeing degradation caused by wind turbulence, the air flow across the enclosure must be measured to develop a realistic three-dimensional velocity profile.

Once the thermal and aerodynamic characteristics are more fully understood, the enclosure can be used as a tool for general research into the effects of enclosures on telescope performance. The capability to stop the enclosure in any position within its range of travel is particularly useful for this research. For example, the effects of dome slits on seeing can be characterized through a comparison of images taken when the roof is below the level of the mirror with similar images taken with the roof above mirror level. Also, a comparison of images taken with the mirror immersed in the enclosure thermal boundary layer to images taken with the mirror above the boundary layer can give some measure of the effects of the thermal boundary layer. Through these studies, the 3.5-m telescope enclosure can be used as a tool in the development of future enclosures.